

# Evidence for a magnetic neutron star in high mass X-ray binary 4U 2206+54 with INTEGRAL/IBIS observations

Wei Wang<sup>\*</sup>

*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*

15 June 2009

## ABSTRACT

The hard X-ray source 4U 2206+54 is a peculiar high mass X-ray binary with a main-sequence donor star. Recent X-ray observations suggested that the compact object in 4U 2206+54 may be a neutron star. The X-ray emission comes from the accretion of stellar winds from the massive donor stars, and variability of luminosity may be due to the changes of its orbit phase. To further reveal the nature of compact object, we studied 4U 2206+54 with INTEGRAL/IBIS observations in two years, and found that in most time, 4U 2206+54 undergone a quiescent state and sometime an active state. In the quiescent state the spectrum can be fitted by a power-law model of  $\Gamma \sim 2.1$  with a hard X-ray luminosity of  $\sim 5 \times 10^{34}$  erg s<sup>-1</sup> (20– 100 keV). While in the active state, the 20– 100 keV hard X-ray luminosity reaches  $\sim 2 \times 10^{35}$  erg s<sup>-1</sup> and the spectrum is fitted by a thermal bremsstrahlung model of  $kT \sim 43$  keV plus two cyclotron absorption lines at  $\sim 30$  and 60 keV. Then we derived a magnetic field of  $3.3 \times 10^{12}$  G for the compact object in 4U 2206+54. During the active state, we found a pulsation period of  $\sim 5400$  s in the light curve of 4U 2206+54. So the compact object in 4U 2206+54 should be a magnetic neutron star with a slow pulsation. Cyclotron absorption lines detected in the active state and non-detection in the quiescent state suggested that two different accretion states have possible different hard X-ray emission regions: surface of neutron star in the active state; the magnetic-accretion pressure equivalent point in the quiescent state. The re-analysis of the RXTE/ASM light curve found the modulation periods at  $\sim 9.56$  days and 19.11 days, and the orbit period of 4U 2206+54 should be 19.11 days.

**Key words:** stars: individual (4U 2206+54) – stars: neutron – magnetic fields – stars : binaries : close – X-rays: binaries.

## 1 INTRODUCTION

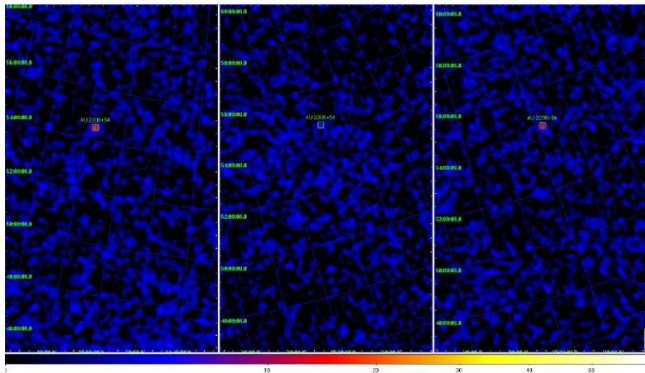
The X-ray source 4U 2206+54 has been studied with numerous ground and space-based observations, but the nature of this source and origins of its variability pattern are still unclear. 4U 2206+54 was identified with an optical counterpart BD +53 2790 by Steiner et al. (1984) which was initially classified as a Be star. However, in optical and UV bands the emission spectrum is complex, in particular the behavior of the H $\alpha$  emission line, suggesting that this star is an O9.5V star (Negueruela & Reig 2001; Ribó et al. 2006; Blay et al. 2006) with a high He abundance (Blay et al. 2006).

X-ray monitoring of 4U 2206+54 by RXTE suggested a modulation period of 9.6 days (Corbet & Peele 2001) which may be an orbit period, but this period disappeared with recent SWIFT/BAT observations (Corbet et al. 2007) which

instead found a modulation of 19.25 days consistent with twice the 9.6-day period. Since there is no circumstellar disc around the donor of 4U 2206+54, the material needed for accretion and production of X-rays should come from the stellar wind. The observed X-ray luminosity of 4U 2206+54 varies from  $10^{33} - 10^{35}$  erg s<sup>-1</sup> from the RXTE, BeppoSAX, SWIFT and INTEGRAL light curves between 1996 and 2005 (Torrejon et al. 2004; Masetti et al. 2004; Blay et al. 2005; Corbet et al. 2007). Ribó et al. (2006) found a low wind terminal velocity of  $\sim 350$  km s<sup>-1</sup> in 4U 2206+54. With such a low wind terminal velocity, and assuming an eccentric orbit, one could reproduce the X-ray luminosity and orbit variability of the system (Ribó et al. 2006).

The nature of the compact object in 4U 2206+54 has been in dispute for a long time (Negueruela & Reig 2001; Corbet & Peele 2001). Broad band X-ray observations and radio studies on 4U 2206+54 favored the presence of a neutron star (Torrejon et al. 2004; Blay et al. 2005). Recent

<sup>\*</sup> E-mail: wangwei@bao.ac.cn



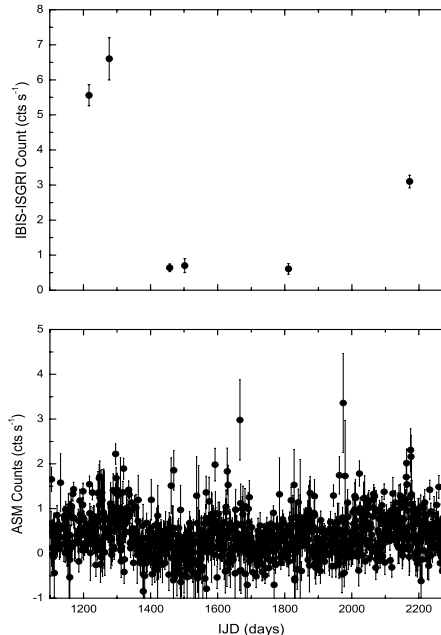
**Figure 1.** Significance mosaic maps around 4U 2206+54 in Equatorial J2000 coordinates as seen with INTEGRAL/IBIS in the energy range of 20 - 60 keV during three observational time intervals (from left to right, detection significance level also noted): 2003 May 2 ( $\sim 17\sigma$ ); 2003 Dec 13 to 31 ( $\sim 5\sigma$ ); 2005 Dec 5 to 12 ( $\sim 20\sigma$ ). False color representation of significance is displayed on a logarithmic scale.

reports on the possible detection of electron cyclotron resonant absorption line at  $\sim 30$  keV suggested a magnetic field of  $\sim 3 \times 10^{12}$  G by different observations of RXTE, BeppoSAX and INTEGRAL (Torrejon et al. 2004; Masetti et al. 2004; Blay et al. 2005). Non-detection of pulsation in 4U 2206+54 was always used as a doubt on the neutron star scenario. Recently, a possible 5500-s pulsation period in the light curve of 4U 2206+54 was discovered with the RXTE observations (Reig et al. 2009). If it is true, the compact object in 4U 2206+54 will be a neutron star with a spin-period of 5500 seconds.

In this work, we will study hard X-ray characteristics of 4U 2206+54 with the INTEGRAL/IBIS observations from 2003 May to 2005 December. Then we can show the hard X-ray spectral properties both in quiescent states (average X-ray luminosity  $\sim 10^{34}$  erg s $^{-1}$ ) and active states ( $> 10^{35}$  erg s $^{-1}$ ). Two cyclotron resonant absorption lines (fundamental and first harmonic) were found in the spectrum of the active states during 2005 Dec, while in the quiescent states, no cyclotron line features are detected. The existence of cyclotron absorption lines suggested a strong magnetic field in 4U 2206+54, and the high energy emission in active states would mainly come from magnetosphere near the neutron star. Therefore, it is possible that we could search for a pulsation period from the light curve of 4U 2206+54 in active states during 2005 Dec with INTEGRAL/IBIS observations. Finally, in order to confirm the existence of the orbit period in X-ray binary 4U 2206+54, we also re-analyzed the archival data of the All Sky Monitor (ASM) aboard RXTE from 1997 to 2008 to search for the orbit period.

## 2 OBSERVATIONS

The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 2003) is ESA's currently operational space-based hard X-ray/soft gamma-ray telescope. There are two main instruments aboard INTEGRAL, the imager IBIS (Ubertini et al. 2003) and the spectrometer SPI (Vedrenne et al. 2003), supplemented by two X-ray monitors JEM-X (Lund et al. 2003) and an optical monitor OMC



**Figure 2.** **Top:** The light curve of X-ray binary 4U 2206+54 in the energy range of 20–60 keV from IBIS observations from 2003 May to 2005 Dec. The time unit is the INTEGRAL Julian date (IJD) starting at 1 Jan 2000. **Bottom:** The light curve of X-ray binary 4U 2206+54 in the energy range of 1.5–12 keV from 2003 May to 2005 Dec from the RXTE/ASM data.

(Mas-Hesse et al. 2003). All four instruments are co-aligned, allowing simultaneous observations in a wide energy range.

4U 2206+54 was observed during the INTEGRAL surveys of the Cygnus and Cassiopeia regions. 4U 2206+54 cannot be detected by JEM-X which has a smaller field of view (FOV), and SPI has the largest FOV but larger uncertainties compared with IBIS, so we only use IBIS data for the analysis in this work. The data were collected with the low-energy array called ISGRI (INTEGRAL Soft Gamma-Ray Imager) which consists of a pixellated  $128 \times 128$  CdTe solid-state detector that views the sky through a coded aperture mask (Lebrun et al. 2003). IBIS/ISGRI has a  $12'$  (FWHM) angular resolution and arcmin source location accuracy in the energy band of 15 – 200 keV. In Table 1, we summarize the INTEGRAL revolutions in our analysis. We used the archival data which are available from the INTEGRAL Science Data Center (ISDC).

The analysis was done with the standard INTEGRAL off-line scientific analysis (OSA, Goldwurm et al. 2003) software, ver. 7.0. In this latest version, the energy correction has changed and new calibration laws have been used for the IBIS/ISGRI analysis. The drift of the energy calibration gain and offset with activation and time are much better calibrated at intermediate energies (around 50 keV). This version results in more constant Crab light curve. Individual pointings processed with OSA 7.0 were mosaicked to create sky images according to the methods and processes described in Bird et al (2007). And we have used the 20 – 60 keV band for source detection and to quote fluxes.

We displayed the significance mosaic maps around 4U

**Table 1.** INTEGRAL/IBIS observations of the field around 4U 2206+54. The time intervals of observations in the revolution number and the corresponding dates, the corrected on-source exposure time are listed. And mean count rate and the detection significance level value in the energy range of 20 – 60 keV were also shown.

Rev. Num.	Date	On-source time (ks)	Mean count rate s <sup>-1</sup>	Detection level
67	2003 May 02–04	11	5.6±0.3	17σ
87	2003 Jul 01 – 03	9	6.6 ± 0.4	16σ
142 – 148	2003 Dec 13 – 31	92	0.6±0.1	5.6σ
161 –162	2004 Feb 07 – 12	33	0.7 ± 0.2	5.1σ
262 – 264	2004 Dec 05 – 13	53	0.6±0.1	5.5σ
384 –386	2005 Dec 05 – 13	68	3.3±0.2	20σ

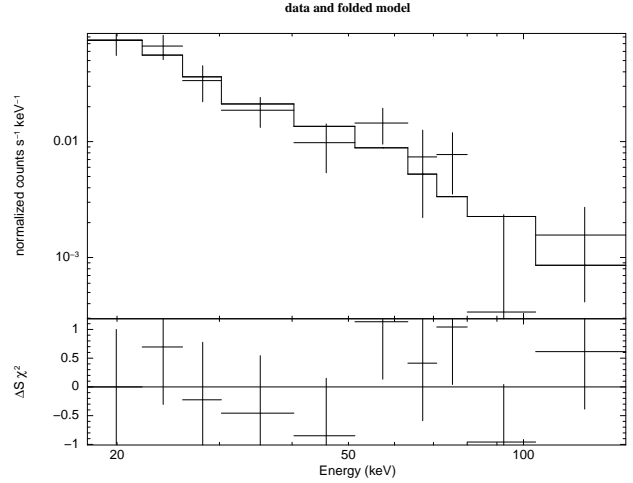
2206+64 as seen with INTEGRAL/IBIS in the energy range of 20 – 60 keV during three observational time intervals in Figure 1 and the light curve of 4U 2206+54 from 2003 May to 2005 December obtained by both IBIS observations in Figure 2 (top). We also presented the light curve of 4U 2206+54 in the energy band of 1.5 –12 keV from the RXTE/ASM long-term monitoring for a comparison (Figure 2 bottom). The count rate from 4U 2206+54 in the energy range of 20 –60 keV varied in more than two years:  $\sim 6$  cts s<sup>-1</sup> on 2003 May 2 and 2003 July 2; and undergoing a quiescent state,  $\sim 0.7$  cts s<sup>-1</sup> around 2003 Dec, 2004 Feb and 2004 Dec; again an active state,  $\sim 3.3$  cts s<sup>-1</sup> around 2005 Dec 5 –13 (also see Table 1).

### 3 SPECTRAL ANALYSIS

The spectral results on the source 4U 2206+54 during the revolutions 67 and 87 with INTEGRAL/IBIS data have been presented in Blay et al. (2005). They reported a possible cyclotron absorption line around 32 keV. Here we will not show the spectral results during these time intervals again, but carry out spectral analyses on the data during the quiescent state and the active state around Dec 2005 respectively. The spectral analysis software package used is XSPEC 12.4.0x (Arnaud 1996).

For the quiescent state, we summed up images from the INTEGRAL resolutions 142 – 148, 161 –162 and 262 – 264 (see Table 1) to improve the detection significance level, and then derived the spectrum which was shown in Figure 3. The 20 – 150 keV spectrum can be fitted with a power-law model of a photon index  $\Gamma \sim 2.1 \pm 0.3$ . The obtained flux in the quiescent state from 20 –100 keV is  $(4.9 \pm 0.9) \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup>, corresponding to a hard X-ray luminosity of  $\sim 5.3 \times 10^{34}$  erg s<sup>-1</sup> assuming a distance of  $\sim 3$  kpc (Blay et al. 2006). No significant cyclotron absorption features were found in quiescence. If assuming the presence of the cyclotron absorption lines at  $\sim 30$  keV (Blay et al. 2005) and  $\sim 60$  keV (see below), we derived the upper limits on the equivalent width (EW) of the absorption lines:  $< 1.6$  keV at 30 keV ( $2\sigma$ ) and  $< 2.4$  keV at 60 keV ( $2\sigma$ ).

The same spectral analysis was carried out during the active state of 4U 2206+54 from Dec 5 to 12, 2005. The derived spectrum was displayed in Figure 4. In the active state, a simple power-law model cannot fit the spectrum, we used a thermal bremsstrahlung model to fit it. However, possible absorption features around 30 and 60 keV cannot be fitted (also seen in the residuals in Figure 4 top panel). Therefore, we used the thermal bremsstrahlung model to fit



wwang 17-Dec-2008 11:41

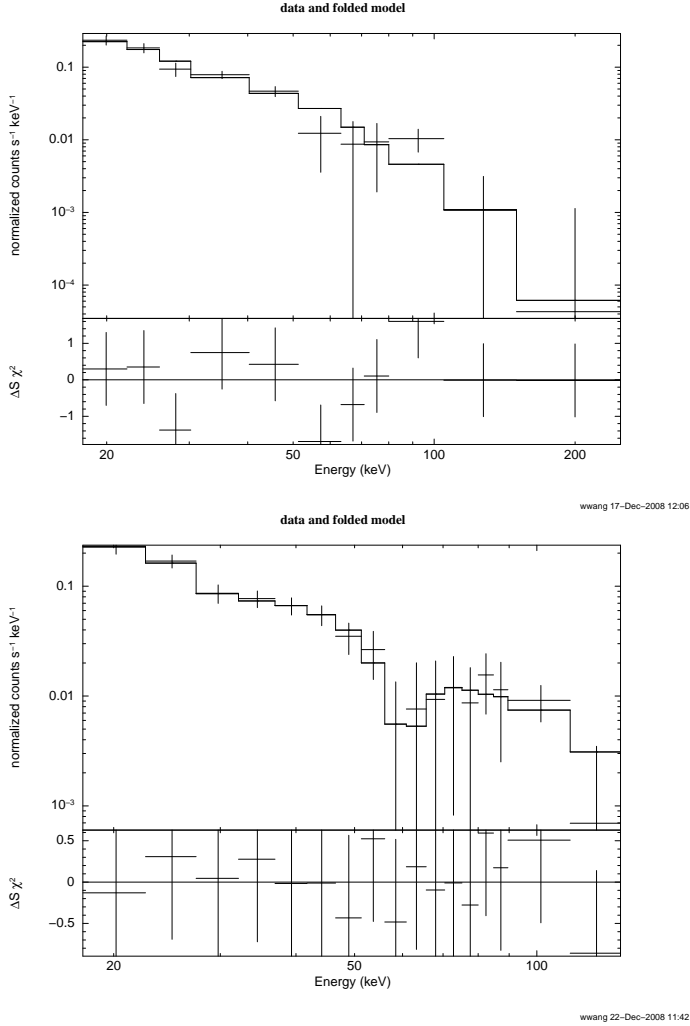
**Figure 3.** The spectrum of 4U 2206+54 in the quiescent state which was derived from the summed mosaic image from the INTEGRAL resolutions 142 – 148, 161 –162 and 262 – 264. The spectrum can be described by a power-law model with a photon index of  $\Gamma \sim 2.1 \pm 0.3$  (reduced  $\chi^2 \sim 0.69$ , 8 d.o.f).

the continuum, and added the cyclotron resonant absorption model by using the XSPEC cyclabs to the continuum fit (see Figure 3). In this case, we found a thermal bremsstrahlung model of  $kT \sim 43.1 \pm 2.0$  keV plus two electron cyclotron resonant absorption lines at  $\sim 29.6 \pm 2.8$  keV (F-test probability:  $2.9 \times 10^{-6}$ ) with a FWHM of  $\sim 1.8 \pm 0.5$  keV and  $\sim 59.5 \pm 2.1$  keV (F-test probability:  $4.2 \times 10^{-10}$ ) with a FWHM of  $\sim 3.9 \pm 0.9$  keV (reduced  $\chi^2 \sim 0.95$ , 6 d.o.f). The derived EW is  $\sim 2.2 \pm 0.7$  keV at  $\sim 30$  keV and  $\sim 9.1 \pm 1.7$  keV at  $\sim 60$  keV separately.

The obtained flux from the 20 – 100 keV continuum during the active state in 4U 2206+54 is  $\sim (2.1 \pm 0.1) \times 10^{-10}$  erg cm<sup>-2</sup> s<sup>-1</sup>, corresponding to a hard X-ray luminosity of  $\sim 2.3 \times 10^{35}$  erg s<sup>-1</sup>.

It is the first time that we detected both the fundamental and second harmonic of the cyclotron resonant absorption lines in the X-ray binary 4U 2206+54. The detection of the line feature at  $\sim 30$  keV also confirmed the previous reports from different measurements (Torrejon et al. 2004; Massetti et al. 2004; Blay et al. 2005). Discovery of the cyclotron resonant absorption lines at  $\sim 30$  and 60 keV strongly suggested a magnetic neutron star located in the binary 4U 2206+54.

We can calculate the value of the magnetic field of the neutron star in 4U 2206+54 by using the formula



**Figure 4.** The spectrum of 4U 2206+54 in the active state from Dec 5 to 12, 2005. **Top** the spectrum only fitted with a thermal bremsstrahlung model of  $kT \sim 37.9 \pm 1.2$  keV (reduced  $\chi^2 \sim 1.68$ , 9 d.o.f). The possible absorption features around 30 keV and 60 keV cannot be fitted well. **Bottom** the spectrum (re-binned for better line fits) can be fitted by a thermal bremsstrahlung model of  $kT \sim 43.1 \pm 2.0$  keV plus two cyclotron resonant absorption lines at  $\sim 29.6 \pm 2.8$  keV and  $\sim 59.5 \pm 2.1$  keV (reduced  $\chi^2 \sim 0.95$ , 6 d.o.f).

$$[B/10^{12}\text{G}] = [E_{\text{cycl}}/11.6\text{keV}](1+z), \quad (1)$$

where  $E_{\text{cycl}}$  is the energy of the fundamental line, here  $E_{\text{cycl}} = 29.6$  keV, and  $z$  is the gravitational redshift near the surface of the neutron star. For a canonical neutron star of  $1.4 M_{\odot}$  with a radius of 10 km, we can take  $z \sim 0.3$  (Kreykenbohm et al. 2004). So we obtain a magnetic field of  $3.3 \times 10^{12}$  G for the neutron star in 4U 2206+54, and this value is still in agreement with those in the previous studies (Torrejon et al. 2004; Massetti et al. 2004; Blay et al. 2005).

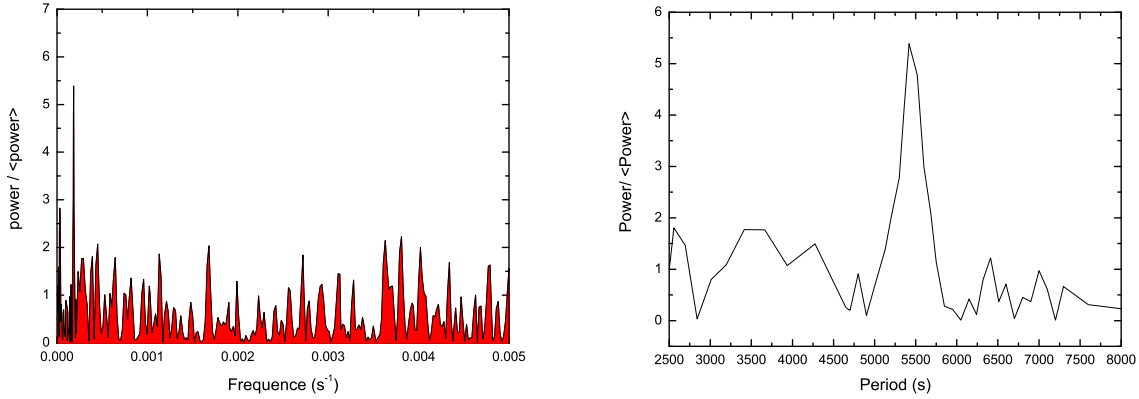
#### 4 SEARCHING FOR THE PULSATION AND ORBIT PERIODS

The high mass X-ray binary 4U 2206+54 shows a variable X-ray light curve. Intensive searches for the pulsation period

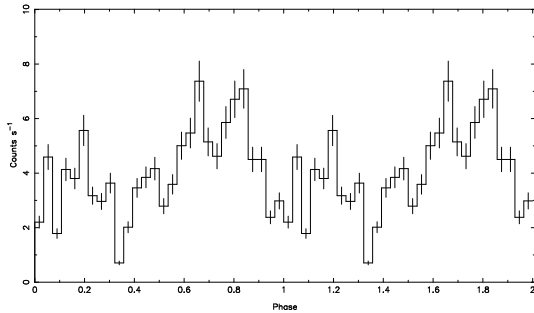
of 4U 2206+54 have been performed with EXOSAT (Corbet & Peele 2001), RXTE (Negueruela & Reig 2001; Torrejon et al. 2004; Corbet et al. 2007), BeppoSAX (Torrejon et al. 2004; Massetti et al. 2004) and INTEGRAL (Blay et al. 2005). However, these studies suggested the lack of the X-ray pulsation on timescales from  $\sim 1$  ms to 1 hr. Recently, Reig et al. (2009) use the new RXTE observational data to search for the pulsation period longer than 1 hr, and discovered a possible 5500-s pulsation period in the light curve of 4U 2206+54. In addition, the early RXTE/ASM data suggested a modulation period of  $\sim 9.6$  days (Corbet & Peele 2001), but the SWIFT/BAT data reported a period of  $\sim 19.25$  days (Corbet et al. 2007), so that Corbet et al. (2007) suggested the orbit period should be 19.25 days instead of 9.6 days. Here we will check these period reports with recent data of INTEGRAL/IBIS and RXTE/ASM.

We have reported the cyclotron resonant absorption line features during the active state in 4U 2206+54, suggesting that during the active state, the X-ray emission mainly coming from the surface of the neutron star. So we try to search for a pulsation period using the light curve data during the active state. We applied the FFT to the observational intervals from Dec 5 to 12, 2005. The power spectrum was shown in Figure 5, binned at 100 s intervals. A significant period signal was found at  $\sim 5400^{+300}_{-200}$  s (Figure 5 right). This period is a little lower than that reported by Reig et al. (2009), but still consistent considering the error bar range. Thus, 4U 2206+54 should be a X-ray pulsar with a very slow pulsation. The folded light curve of 4U 2206+54 at a pulsation period (5400 s) is also shown in Figure 6. A possible double main peak feature appears in the pulse profile, one at  $\sim 0.2$  and the other around  $0.6 - 0.9$ .

Since the available database during the active state is limited to less than 7 days, we cannot search for the longer modulation period (like orbit period, possible  $\sim 9.6$  d or 19.2 d) with the INTEGRAL database during the active state of 4U 2206+54. We used archival RXTE/ASM data with observations from 1997 – 2008 to search for the orbit period in 4U 2206+54. Firstly, we averaged the ASM 1.5 – 12 keV light curves into 1 hour bins. After subtracting the mean value of all inhabited bins from each inhabited bin, we take an FFT to the light curve. The power spectrum is shown in Figure 7. In the top panel of Fig. 7, we have shown a power spectrum in a wider frequency range, and no significant signal was found in the high frequency range ( $< 100$  hours), while two significant peaks were detected in the lower frequency range. Then in the bottom panel, from the zoom-in of the low frequency band, we determined two modulation periods at  $9.56 \pm 0.03$  days and  $19.11 \pm 0.07$  days (twice the former one). So we confirm the existence of the possible orbit periods reported by both the early RXTE/ASM data (Corbet & Peele 2001) and the recent SWIFT/BAT observations (Corbet et al. 2007). In Figure 8, the folded light curves of 4U 2206+54 using the RXTE/ASM data at two modulation periods at 9.56 day and 19.11 day were also displayed separately. A possible peak at  $\sim 33.2$  days also appeared in the power spectrum though not significantly yet, which may be just a noise signal.



**Figure 5.** **Left** Power spectrum of the INTEGRAL/IBIS light curve of 4U 2206+54 during the active state. The significant peak appears around 5000 s. The unit is the resulting power in each frequency bin divided by the average power over the whole frequency range (same in Fig. 6). **Right** The zoom-in of the power spectrum around 5000 s. We determined a period of  $\sim 5400^{+300}_{-200}$  s.



**Figure 6.** The IBIS-ISGRI background subtracted light curve (20 – 60 keV) of 4U 2206+54 folded at a pulsation period (5400 s). The pulse profile is repeated once for clarity.

## 5 CONCLUSION AND DISCUSSION

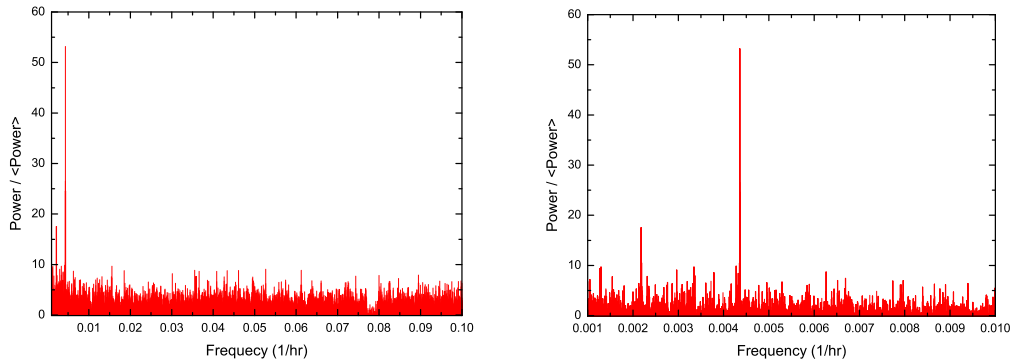
In this paper, we studied the hard X-ray emission of the high mass X-ray binary 4U 2206+54 with INTEGRAL/IBIS observations to reveal the nature of the compact object. In hard X-ray bands, 4U 2206+54 undergone both the quiescent and active states. In the quiescent state, the 20 – 150 keV spectrum of 4U 2206+54 can be fitted by a power-law model with  $\Gamma \sim 2.1$ , and no cyclotron absorption line features are found. While, in the active state, two cyclotron absorption lines at  $\sim 30$  keV and 60 keV are discovered in the hard X-ray spectrum. With known the cyclotron resonant absorption energy, we determined the magnetic field of  $\sim 3.3 \times 10^{12}$  G for the compact object in 4U 2206+54. Analysis of the X-ray light curve during the active state, we also found a modulation period of  $\sim 5400$  s which would be a pulsation period for a neutron star. Thus we identified the compact object in 4U 2206+54 as a magnetic neutron star with a very slow pulsation.

From the ASM light curve of 4U 2206+54, we found two modulation periods of  $\sim 9.56$  days and the twice, 19.11 days. Then which one is the real orbit period in 4U 2206+54? One possibility is that the 19.11-day period is just the first harmonic of the 9.6-day period. But the SWIFT/BAT data

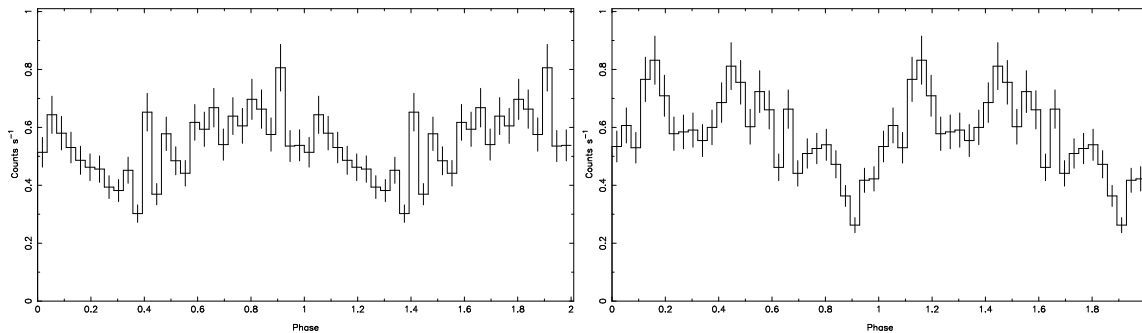
only found one period at 19.2 days, and recent RXTE/ASM data from 2004 – 2006 showed the modulation period at 19.1 days, not significantly at 9.6 days yet (Corbet et al. 2007; we also folded the light curve at 9.6 day using the RXTE/ASM data after 2003, no significant features were detected in phase profiles). Then the 9.6 day period was not a permanent signal in X-ray light curve. Then appearance of 19.2-day period may not be the first harmonic of 9.6 day. In addition, optical radial velocity measurements (Blay et al. 2006) have not shown the period at 9.6 days but the power spectrum of the complete set of radial velocity observations suggested a peak at  $\sim 14.89$  days, which was interpreted as an artifact.

Modulation of X-ray emission on the orbit period in a high mass X-ray binary may occur in different ways as follows. Firstly, if the orbit is eccentric, the peak emission would occur at periastron passage ( $e = 0.15$  assumed by Ribó et al. 2006). In this case, it is difficult to understand why two periods appeared in the X-ray light curve. In addition, an eccentricity of  $\sim 0.4$  was suggested from the X-ray light curve analysis (Reig et al. 2009), so 4U 2206+54 has a modestly eccentric orbit. In the second case, if the orbit plane is inclined to the plane of an equatorial circumstellar disc, two possible outbursts could occur when the neutron star passes through the disc. This scenario has been proposed to explain two modulation periods detected in two X-ray binaries: a Be/neutron star binary GRO J2058+42 (Corbet et al. 1997) and a supergiant system 4U 1907+09 (Mashall & Ricketts 1980). Though 4U 2206+54 has the difference in the nature of the mass donor, the orbit behavior may be similar to the case in GRO J2058+42 and 4U 1907+09. Therefore, we suggested that the orbit period of 4U 2206+54 should be  $\sim 19.11$  days, which was consistent with the conclusion by Corbet et al. (2007).

In hard X-ray band, only the orbit period at  $\sim 19$  days could be found with SWIFT/BAT observations (Corbet et al. 2007), while in soft X-ray band of 1.5 – 12 keV, we found two modulation periods. If the 9.6-day period is due to the neutron star passing through the equatorial plane of the mass donor, soft X-ray emission may be affected by the en-



**Figure 7.** Power spectra of the RXTE/ASM light curve of 4U 2206+54 with observations from 1997 to 2008. The left panel shows the power spectrum in all frequency band. And the right panel presents the zoom-in of the lower frequency band which clearly shows the position of two peaks at  $\sim 9.56$  days and 19.11 days.



**Figure 8.** RXTE/ASM light curves of 4U 2206+54 folded at two possible orbit periods at 9.56 day (left) and at 19.11 day (right).

hanced wind around the disc, but hard X-ray emission has no significant dependence on it. Therefore, the hard X-ray emission above 20 keV and its variation pattern should have a different origin from those in the soft X-ray band, which requires more studies.

In the Be star/neutron star binary systems, there exists a possible correlation between orbit period and pulse period (Corbet 1986). Though 4U 2206+54 have a different mass donor but may be still similar to a Be star system, it is predicted to have a pulse period of a few second for a orbit period of 19.11 days according to the correlation, which however is inconsistent with the pulsation period of  $\sim 5400$  s reported in this work (maybe  $\sim 5560$  s, also see Reig et al. 2009). Two high mass X-ray binary systems also show the similar behavior away from the correlation: A0538-66 with an orbit period of 16.7 days has a short pulse period of 69 ms (Skinner et al. 1982) and SAX J2103.5+4545 with an orbit period of 12.7 days has a longer pulse period of 358.6 s (Baykal et al. 2000). Generally, the 19 day orbit period is relatively short for a Be star system. Therefore, the orbit-pulse period correlation would be invalid at the short orbit period. From pulse period versus orbit period diagram (see Reig et al. 2009), 4U 2206+54 fall into the wind-fed supergiant system region which was consistent with the proposed wind-accretion scenario from the X-ray emission properties (Corbet & Peele 2001; Ribó et al. 2006).

Though we have now confirmed the nature of the compact object in 4U 2206+54, many questions on this high

mass X-ray binary are still unclear, requiring further studies in both theories and observations. Origin of the low-pulsation neutron star in 4U 2206+54 is a mystery according to the present scenario of the neutron star's spin evolution in a close binary system (Davies & Pringle 1981; Li & van den Heuvel 1999). So Reig et al. (2009) suggested that the neutron star in 4U 2206+54 was born as a magnetar with  $B \geq 10^{14}$  G which was used to explain the long pulsation period of 2S 0114+65 (Li & van den Heuvel 1999). Since the donor star of 4U 2206+54 is a main sequence massive star, the magnetic field of the neutron star decaying from  $\geq 10^{14}$  G to  $10^{12}$  G during wind accretion processes within several million years is also questionable. There exist other possible ways to resolve the problems, like X-ray pulsar in 4U 2206+54 may not follow the present standard evolution models in close binaries. Some numerical simulations suggested that no significant angular momentum transfers onto the neutron star from the wind of supergiant systems (Ruffert 1999). In the case of 4U 2206+54 with a magnetic neutron star, it is possible that the calculations (Ruffert 1999) were inapplicable, so that the 5000-s pulsation period was formed during the wind-fed accretion phase.

We discovered cyclotron resonant absorption lines at  $\sim 30$  keV 60 keV in the active state of 4U 2206+54, but no detection of cyclotron lines in the quiescent state. In previous studies, the possible detection of electron cyclotron absorption line at  $\sim 30$  keV was reported by observations of RXTE, BeppoSAX and INTEGRAL (Torrejon et al. 2004;

Masetti et al. 2004; Blay et al. 2005). But recent RXTE observations by Reig et al. (2009) did not find the cyclotron line at  $\sim 30$  keV similar to the quiescent state reported in this paper. Then from the present data, cyclotron lines could be detected when the hard X-ray luminosity (20–100 keV) is higher than  $10^{35}$  erg s $^{-1}$  (also see Blay et al. 2005). We suggested that in the active state (like  $L_{20-100\text{keV}} > 10^{35}$  erg s $^{-1}$ ), hard X-ray emissions will mainly come from the surface (e.g., polar cap region) of the neutron star, while in the quiescent state, the X-ray emission would mainly come from the standing point region where the magnetic pressure is equal to the accretion pressure.

Among the wind-fed massive binary system, 4U 2206+54 is a unique one which was identified as a magnetic neutron star with a very low pulsation. Thus, detailed studies and long-term monitoring of the peculiar neutron star binary 4U 2206+54 in X-rays will help to understand accretion physics and evolution of wind-fed systems.

## ACKNOWLEDGMENTS

The author is grateful to the referee for the fruitful suggestions to improve the manuscript and also to Jiang, Y. Y. for the help to prepare some figures. This paper is based on observations of INTEGRAL, an ESA project with instrument and science data centre funded by ESA member states (principle investigator countries: Denmark, France, Germany, Italy, Switzerland and Spain), the Czech Republic and Poland, and with participation of Russia and US. We used the archival data from ASM Light Curve webpage developed by the ASM team at the Kavli Institute for Astrophysics and Space Research at the Massachusetts Institute of Technology. W. Wang is supported by the National Natural Science Foundation of China under grants 10803009, 10833003.

## REFERENCES

- Arnaud, K.A., 1996, in *Astronomical Data Analysis Software and Systems V*, ASP Conf. Ser., 101, 17
- Baykal, A., Stark, M.J. & Swank, J.H., 2000, *ApJ*, 544, L129
- Bird, A.J. et al., 2007, *ApJS*, 170, 175
- Blay, P. et al., 2005, *A&A*, 438, 963
- Blay, P. et al., 2006, *A&A*, 446, 1095
- Corbet, R.H.D., 1986, *MNRAS*, 220, 1047
- Corbet, R.H.D., Peele, A.G. & Remillard, R., 1997, *IAU circ.*, 6556, 3
- Corbet, R.H.D. & Peele, A.G., 2001, *ApJ*, 562, 936
- Corbet, R.H.D., Markwardt, C.B. & Tueller, J., 2007, *ApJ*, 655, 458
- Davies, R.E. & Pringle, J.E., 1981, *MNRAS*, 196, 209
- Goldwurm, A. et al., 2003, *A&A*, 411, L223
- Kreykenbohm, I. et al., 2004, *A&A*, 427, 975
- Lebrun, F. et al., 2003, *A&A*, 411, L141
- Li, X.D. & van den Heuvel, E.P.J., 1999, *ApJ*, 513, L45
- Lund, N. et al., 2003, *A&A*, 411, L231
- Marshall, N. & Ricketts, M.J., 1980, *MNRAS*, 193, 7P
- Masetti, N. et al., 2004, *A&A*, 423, 311
- Mas-Hesse, J.M. et al., 2003, *A&A*, 411, L261
- Negueruela, I. & Reig, P., 2001, *A&A*, 371, 1056
- Reig, P. et al., 2009, *A&A*, 494, 1073
- Ribó, M. et al., 2006, *A&A*, 449, 687
- Ruffert, M., 1999, *A&A*, 346, 861
- Skinner, G.K. et al., 1982, *Nature*, 297, 568
- Steiner, J.E. et al., 1984, *ApJ*, 280, 688
- Torrejón, J.M. et al., 2004, *A&A*, 423, 301
- Ubertini, P. et al., 2003, *A&A*, 411, L131
- Vedrenne, G. et al., 2003, *A&A*, 411, L63
- Winkler, C. et al., 2003, *A&A*, 411, L1